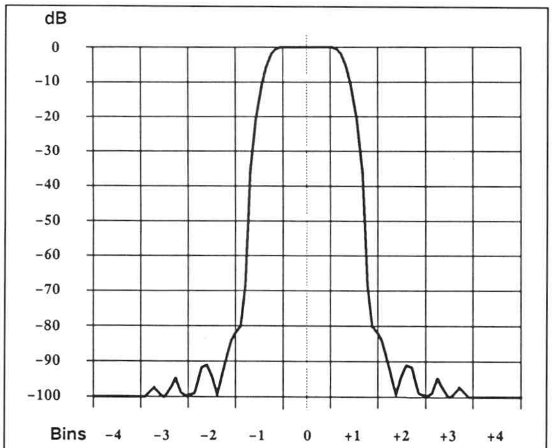
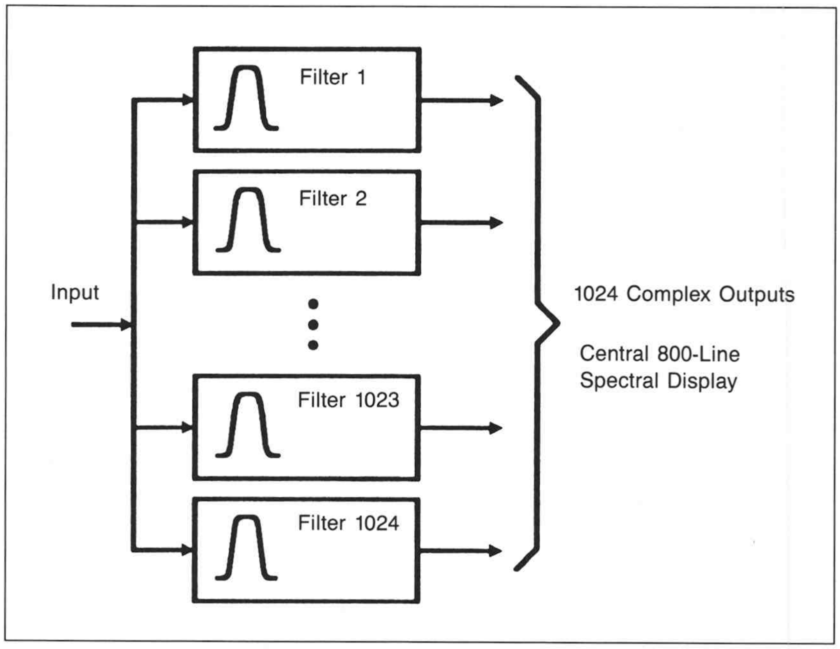
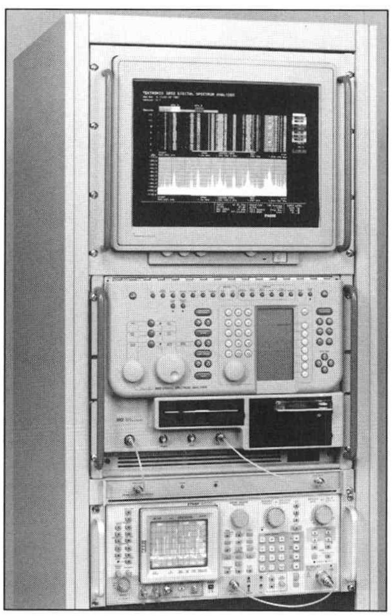
REAL-TIME SPECTRUM ANALYSIS USING DSP TECHNIQUES— A TECHNOLOGY OVERVIEW



FIR Filter Shape





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Digital Signal Processing (DSP) is a Tektronix business unit specializing in high-speed digital spectrum analysis products. These products offer engineers and analysts unparalleled signal modulation analysis capabilities for laboratory and high-throughput manufacturing applications.

Tektronix is a leading manufacturer of electronic products and systems in the areas of test and measurement, computer graphics, and communications. The company has approximately 16,000 employees worldwide, and sales exceed $1.4 billion.

Advances in Real-Time Spectrum Analyzer Technology

An oscilloscope only tells half the story about any waveform, the time-domain chapter. The other half of the story, the frequency domain chapter, is necessary for both a full understanding and a complete description of any waveform. In fact, the frequency domain information often turns out to be the more important part in many applications.

Frequency content and relationships are particularly important in analyzing communication channel characteristics, acoustical phenomena, mechanical vibration, radar and laser pulse characteristics, information encoding schemes, and waveforms from a host of other diverse applications. Often, conventional spectrum analyzers can provide the necessary frequency domain information.

However, in the past few years, there's been an increasing number of applications that demand more complete spectral coverage. And in many instances, the coverage has to be done in real time. For example, testing or monitoring data encryption schemes and other frequency agile applications almost always requires real-time frequency analysis. This is because the frequencies are mobile; they hop around the spectrum. In many other cases, real-time analysis is necessary simply because the event of interest is a short-lived transient—a data channel error, a spurious radar return, or an impact-related acoustic emission, to name a few examples.

Until recently, technical difficulties in achieving real-time spectrum analysis have placed severe limitations on the amount of information obtainable in a wide range of applications. Now, with new innovations in digital filter banks, real-time and high-speed spectrum analysis capabilities have been significantly expanded. Compared to previous technology, conversion rates have been increased nearly 100 fold for DC to 10-MHz coverage, and available real-time bandwidths have been extended from a few tens of kilohertz to 2 MHz.

The core analysis and processing technology necessary to achieve these capabilities was initiated and originally developed in the Electronic Systems Laboratory of Tek Labs, the Tektronix central research organization. This technology and its capabilities have been incorporated in the Tektronix 3052 Digital Spectrum Analyzer along with other extensive processing and display capabilities by the Digital Signal Processing Unit at Tektronix.

The result of these innovations is a whole new realm of spectrum analysis power. But to appreciate the true significance of this power, it's necessary to step back and review some frequency-domain and spectrum analysis basics. Along with this, a greater understanding of the related measurement applications and problems will serve to better illustrate the importance of the new spectrum analysis capabilities of the 3052 Digital Spectrum Analyzer.

Some Spectrum Basics

There are basically two ways to describe or view waveforms representing physical events or phenomena. The event or waveform description can be in the time domain, or it can be in

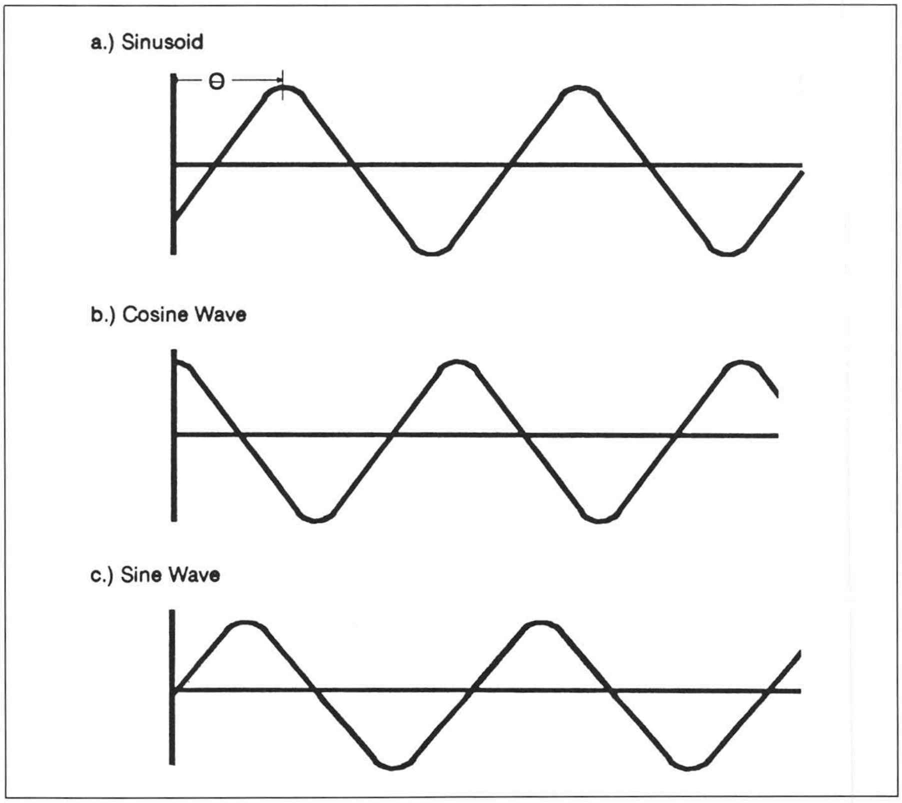


Figure 1. Representations of various sinusoids in the time domain with distinctions made by phase relative to time zero.

the frequency domain. The most familiar of these is the time domain, which is a description of amplitude versus time. An example of this method of description is shown in Figure 1.

The waveform in Figure 1a is often referred to as a sine wave. This is because it follows the general form of the function given by $A * \sin(2\pi ft)$. However, to be rigorous, the waveform in Figure 1a is more generally a sinusoid since it has an arbitrary phase (θ) relative to the time-zero reference. For the specific case of zero phase (Figure 1b), the sinusoid is, by definition, a cosine wave $\{A * \cos(2\pi ft)\}$. A cosine wave delayed by 90° or $\pi/2$ radians, as shown in Figure 1c, is by definition a sine wave $\{A * \sin(2\pi ft) = A * \cos\{2\pi ft - \pi/2\}$. From these simple definitions, it is relatively easy to create equivalent frequency-domain diagrams for the same waveforms. These diagrams, shown in Figure 2, are plots of magnitude versus frequency and phase versus frequency. Each magnitude and phase component is represented by a spectral line. For pure sinusoids, there is one set of magnitude and phase lines. For nonsinusoidal waveforms of a continuous or repetitive nature, there are multiple sets of lines representing the various frequency components in the waveform. And, in the case of a transient or single-shot signal, the spectral lines merge to form a continuum of spectral energy.

The phase relations shown in Figure 2 are based on using the cosine definition as the zero-phase reference. All other sinusoids or frequency components are expressed as phase shifted versions of the cosine wave. Thus the cosine frequency-domain representation has zero phase, the sine wave has −90° phase, and all other sinusoids have phase θ corresponding to their shift (advance or delay) from the cosine wave reference.

The frequency-domain descriptions in Figure 2 are in polar form. They could just as well be expressed in a rectangular form consisting of real and imaginary parts. The conversion is illustrated in Figure 3 and serves to point out the interrelatedness of sine and cosine terms (or coefficients) in describing any waveform, including a sinusoid. Indeed, it is this real and imaginary form that is most often used in mathematical transformations and treatments in the frequency domain. The classical transforms, of course, are the Laplace and Fourier transforms. Both of these transforms provide mathematical conversions between time-domain functions and complex functions (having real and imaginary parts) of the frequency domain.

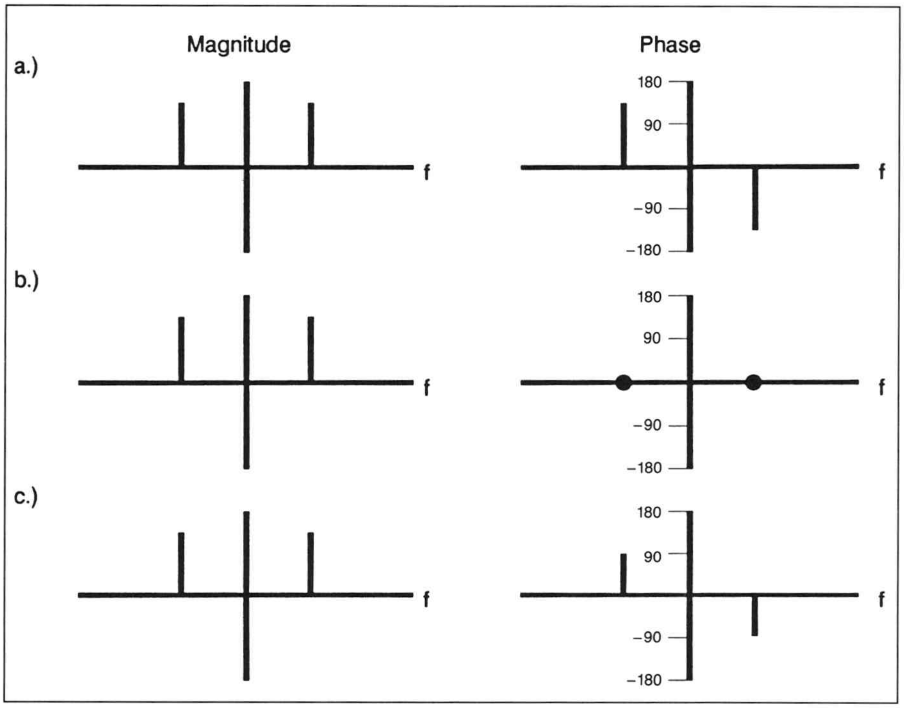


Figure 2. Frequency-domain diagrams corresponding to the sinusoids in Figure 1.

The examples illustrated thus far have been of a single-frequency, purely sinusoidal nature. That is, they represent a pure tone. More typically, the waveforms dealt with in real life are not pure tones. Instead, they are made up of combinations of sinusoids having unique amplitude and phase relationships that govern the time-domain shape of the waveform (Figure 4). The goal of spectrum analysis is to be able to look at these general waveshapes in terms of their constituent sinusoids (frequency components or spectral lines).

A simple example of the value of spectrum analysis is the case of determining the purity of a sinusoid. Small distortions from a purely sinusoidal shape are generally imperceptible in the time domain. However, in

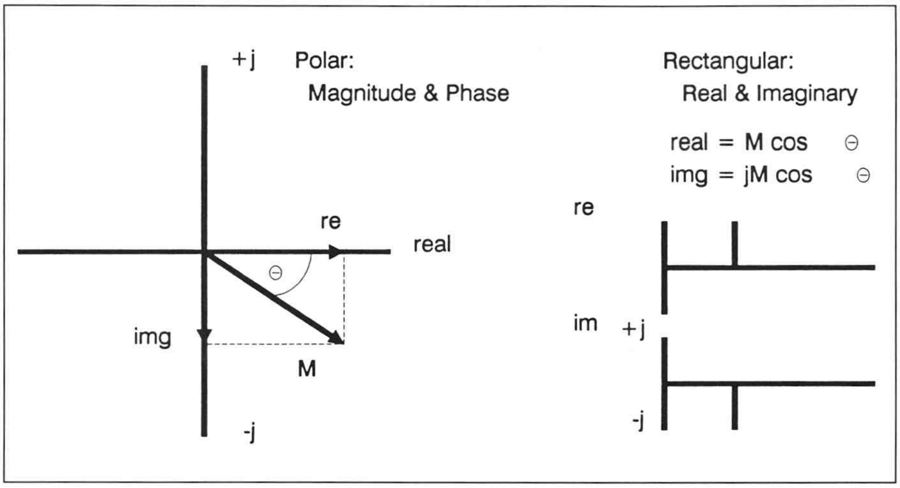


Figure 3. The polar and rectangular forms for expressing complex data pairs.

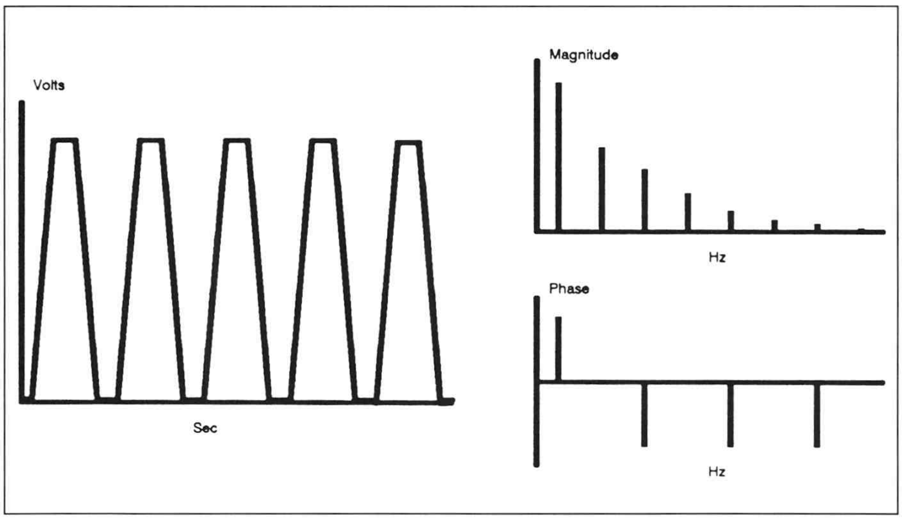


Figure 4. Nonsinusoidal waveforms are made up of numerous sinusoids having various frequencies, magnitudes, and phases.

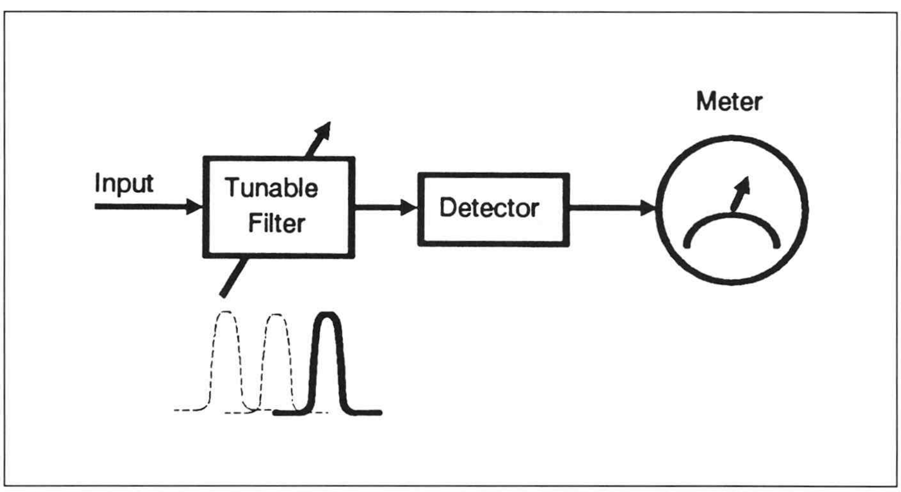


Figure 5. A tuned voltmeter can be used for narrow band analyses.

the frequency domain, the distortions become quite apparent as harmonic components. Another example is looking at the sideband characteristics of an amplitude modulated signal, or even the frequency stability of the carrier. All of these signal attributes and many more are most readily distinguishable and measurable in the frequency domain.

The challenge, however, is to somehow transform or convert normally occurring time-domain phenomena—waveform—to the frequency domain.

Spectrum Analyzer Trends

Historically, the challenge of obtaining frequency-domain information has been met with analog filters. For example, a tuned voltmeter uses a narrow band tunable filter at its input (Figure 5). The signal to be analyzed is applied to the filter, and the filter is slowly tuned through its range. By noting the frequencies to which the filter is tuned and the corresponding meter readings of amplitude, the composition of the input signal can be determined in terms of frequencies and their relative magnitudes. Generally, such tuned filter methods are restricted to narrowband analysis because of analog filter tuning and response limitations.

For wider band analyses, multiple fixed filters can be used in parallel. Then, rather than sweeping the filter's tuning, the detector circuit is swept across the bank of fixed filters as shown in Figure 6. Generally, the fixed filters used in this method have 1/3-octave center frequency spacings with closely adjacent or overlapped filter bandwidths. This 1/3-octave technique gives rise to spectral displays presented in a bar graph format.

A more sophisticated spectrum analysis approach uses an input mixer and a swept-frequency local oscillator to convert the input signal to a swept IF (intermediate frequency). This swept IF can then been applied to a fixed filter, as shown in Figure 7, and the output used to drive a CRT display of the signal's frequency spectrum. This is the fundamental approach used by most conventional spectrum analyzers. However, in most modern spectrum analyzers, the approach has been considerably expanded to included several heterodyning IF stages and different resolution bandwidth filters. The advantage of the heterodyning approach is that it is amenable to broadband applications, from Hertz to GigaHertz. The frequency spans and filter resolutions are also selectable for varying degrees of narrow band analyses around any selected center frequency— all in a single instrument.

Most modern heterodyning spectrum analyzers also employ considerable digital technology to enhance their analysis capabilities. The swept analog spectrum is often digitized and stored in digital memory. This allows several spectral displays to be captured at different times and compared. Intelligent marker systems have also been included for automatically searching out peaks, next higher or lower peaks, bandwidth points, and other salient spectral features. Additionally, these analysis features have been combined with substantial digital control and programming capabilities that allow a wide range of measurement automation, either from internally stored push-button macro programs or from external software running on low-cost personal computers.

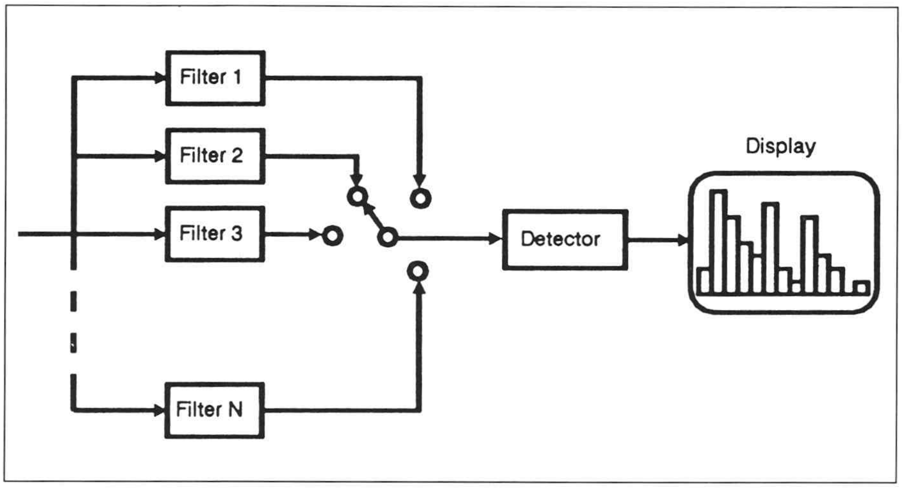


Figure 6. Using step-selected parallel filters for spectral analyses.

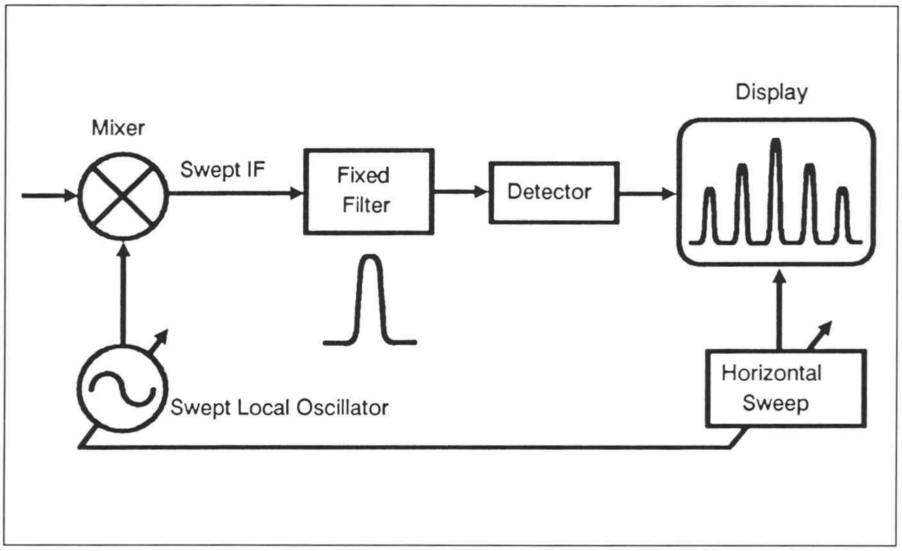


Figure 7. Heterodyning spectrum analyzers use fixed filters and swept IF stages for broad band analyses.

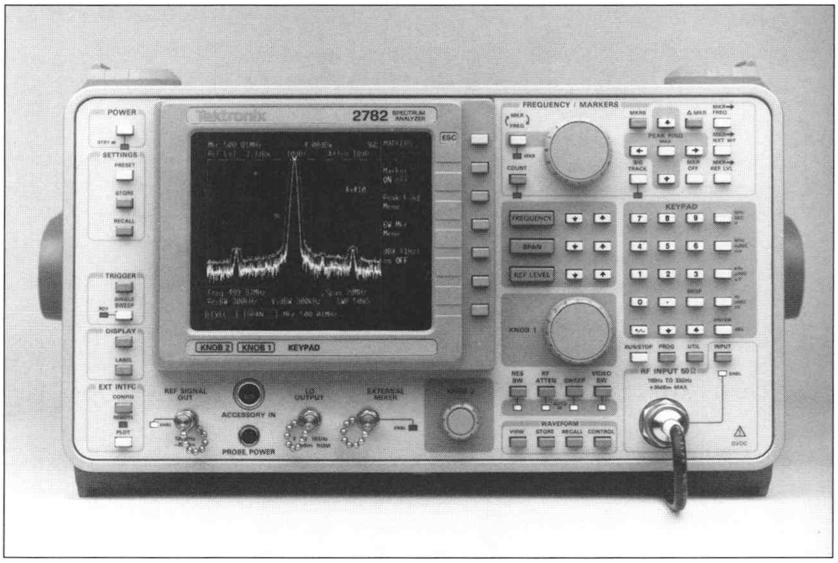


Figure 8. Heterodyning spectrum analyzer.

With the advent of economical digital technology and computing power, an alternative to analog filter methods became available. This alternative is the FFT (fast Fourier transform) approach shown in Figure 9. The FFT is a signal processing algorithm that allows complete spectral analysis of digitized waveforms. Its advantage is that any signal that can be digitized can be transformed to a complete description in the complex frequency domain. Even short lived transients signals can be transformed if they are captured with sufficient digital points to define the transient.

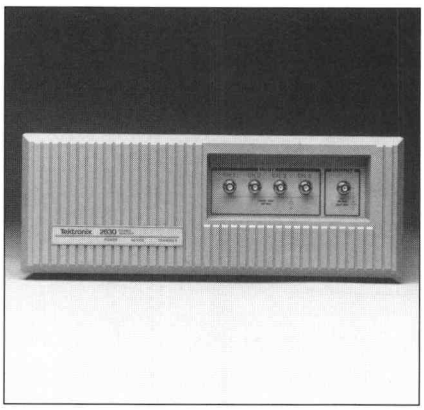


Figure 9. Example of FFT analyzer application is mechanical measurements.

Algorithmic FFT computation of frequency domain components is complete in that it provides the complex frequency domain (real and imaginary or magnitude and phase for each frequency). By contrast, conventional or analog spectrum analyzers typically only provide frequency magnitude and neglect phase. The advantage of the complex frequency domain over this is that a wide range of other analysis capabilities become available. These include convolution, correlation, transfer function analysis, and other processes that rely on real and imaginary components for computation.

Unfortunately, both the spectrum analyzer and FFT approaches to the frequency domain share a common limitation. For different reasons, they are both restricted on how often they can look at or provide a view of the frequency domain. This limits their use in many real-time frequency monitoring applications.

In the case of swept filter and heterodyning analyzers, the real-time restriction is a function of the sweeping rate and how often a sweep is triggered. Information at any given frequency is only updated when the analyzer's filter is tuned to that frequency.

The FFT has the same shortcoming. It provides output for each frequency only at widely spaced intervals of time. This update rate is a function of FFT processing times. An FFT analyzer digitizes an analog signal into blocks of data, or records, that can be thought of as snapshots of the signal. After the block is acquired int odigital memory, it is processed by the FFT to obtain a block, or record, of spectral data. The speed of all necessary block transfers and processing determines how often a new snapshot of data can be acquired and processed into a corresponding updated snapshot of the spectrum.

With current FFT Analyzer technology the fastest update rate is about 20 ms for a complex 1024-point FFT. In other words, an FFT instrument can revisit each frequency once every 20 ms at best. For continuous time-domain sampling and conversion to the frequency domain without gaps in spectral information, the corresponding real-time FFT analyzer bandwidth ceiling is about 80 kHz.

An 80-kHz real-time ceiling is far too low for many of today's real-time application requirements. To break this barrier, Tektronix has developed a new approach to real-time conversion that is based on a parallel bank of digitally implemented filters. The update rate of this new technology is 200 μs. This is 100 times faster than current FFT Analyzer technology.

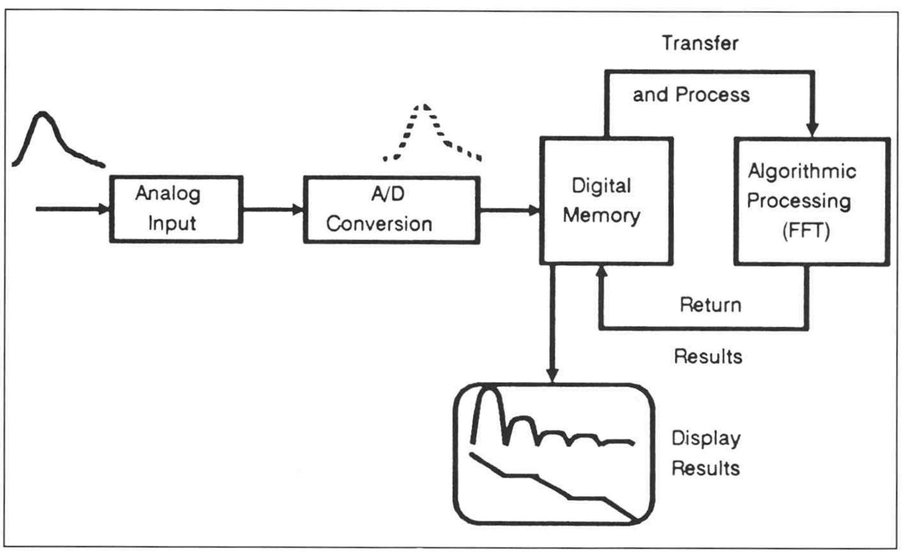


Figure 10. Spectrum analysis via waveform digitizing and the FFT (Fast Fourier Transform) method.

Expanding Needs for Real-Time Analysis

Today there is a growing need for monitoring and measuring frequency spectra in real time. Some of the key real-time application areas include monitoring systems for spurious outputs, tracking frequency-hopping transmitters, characterizing data channels during bit-error conditions, and general surveillance for unwanted or abnormal spectral occurrences.

In order to view the frequency content of such signals in real time, **the update rate for each frequency must be twice the resolution of the analyzer**. For example, to cover a 2-MHz span with 2.5-kHz resolution in real time, the analyzer must provide spectral frame updating every 200 μS (a 5-kHz rate).

This real-time application requirement is specifically addressed by the new high-speed filter bank analysis approach developed by Tektronix. This filter bank approach allows real-time spectral analysis to 2 MHz and nearly real-time analysis to 10-MHz. This capability, available only in the new 3052 Digital Spectrum Analyzer, expands real-time spectral analysis bandwidth by two orders of magnitude over that available with current FFT analyzer technology. Moreover, with a user-supplied block down converter, the 10-MHz bandwidth of the 3052 Digital Spectrum Analyzer can be applied well into the microwave frequencies.

The Digital Filter Bank Approach

A general overview of the Tektronix 3052 Digital Spectrum Analyzer is provided by the block diagram in Figure 11.

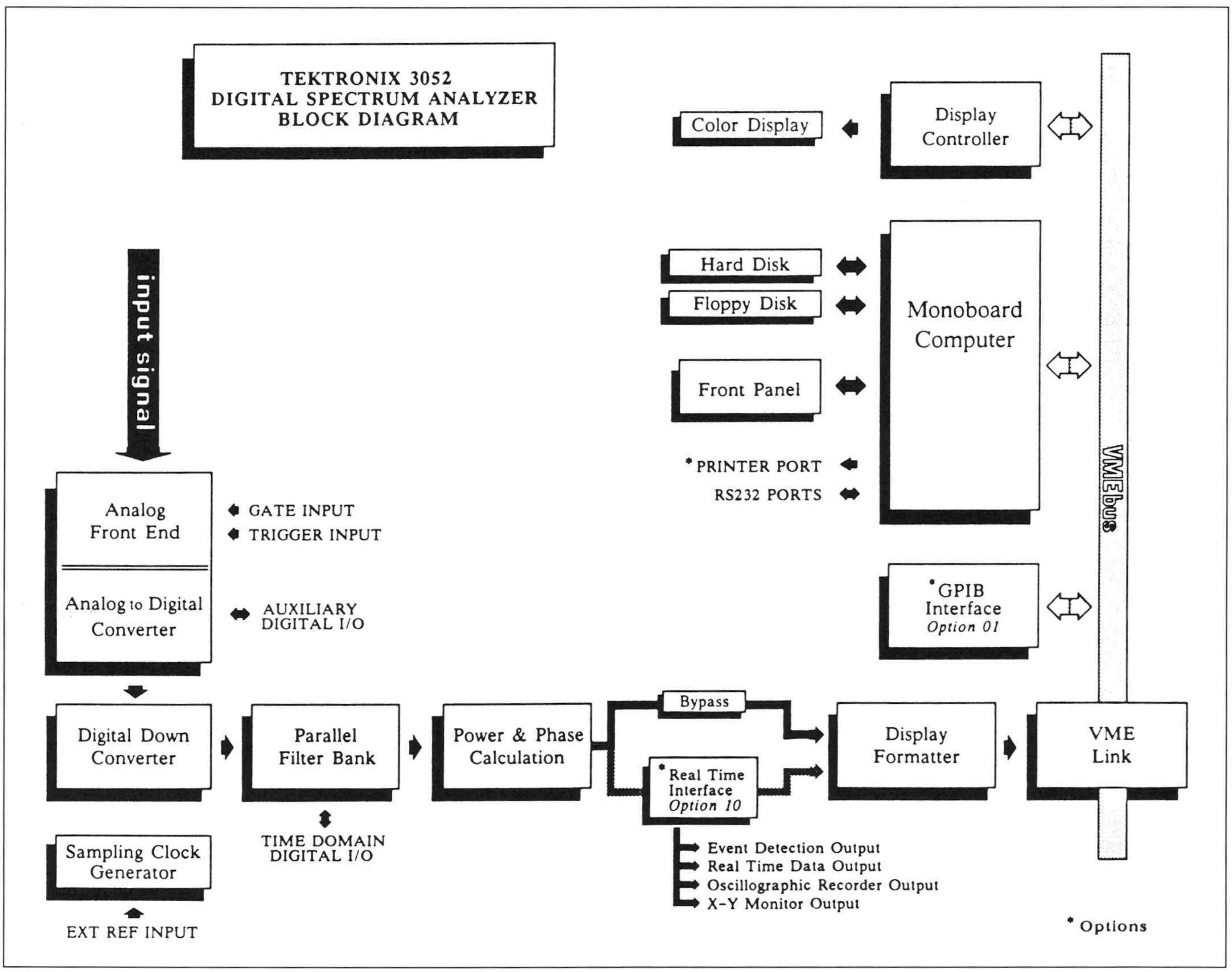


Figure 11. Block diagram of the Tektronix 3052 Digital Spectrum Analyzer.

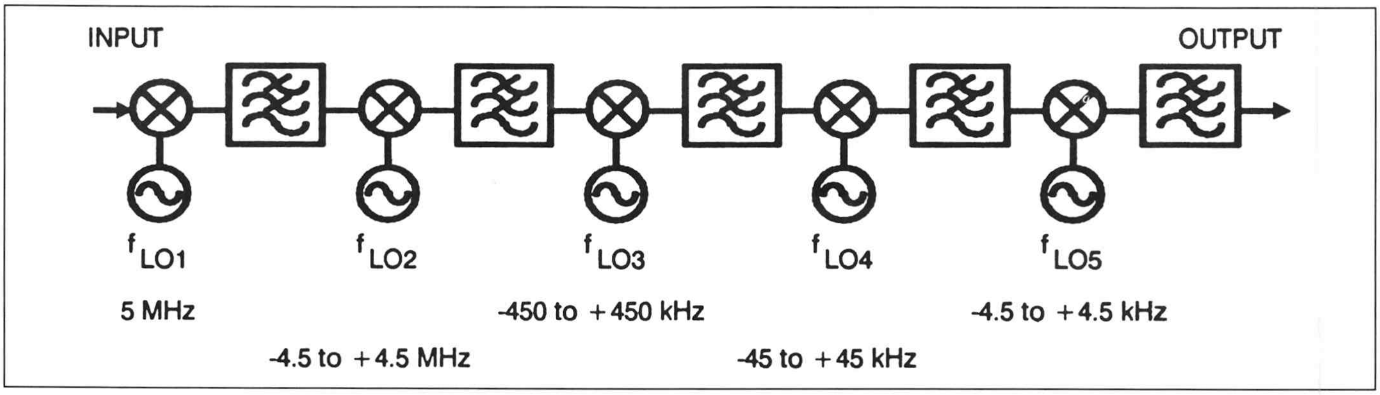


Figure 12. The Digital Down Converter stages used for span and center frequency selection.

The key elements for the new 2-MHz real-time capability are the digital down converter and filter bank.

Time-domain signals to be analyzed are applied to the analog front end of the 3052 and digitized. The digitized input signal is fed to the Digital Down Converter (DDC). There are five DDC stages that are used or bypassed to provide 13 span selections from 1 kHz to 10 MHz in a 1-2-5-10 sequence (see Figure 12). These stages also provide tunable center frequency selection and low-pass antialias filtering.

The time-domain output of the DDC is applied to the filter bank, which consists of 1024 finite impulse response (FIR) filters in parallel. This bank of filters transforms the down converted time-domain data to the complex frequency domain. The result is a 1024-point complex spectral frame (Figure 13). Of these 1024 points, or spectral lines, the central 800 are used for presentation of the spectral frame.

To obtain exceptionally high conversion speeds, this filter bank approach is implemented with VLSI chips and parallel processing. The overall result in processing speed is billions of operations per second.

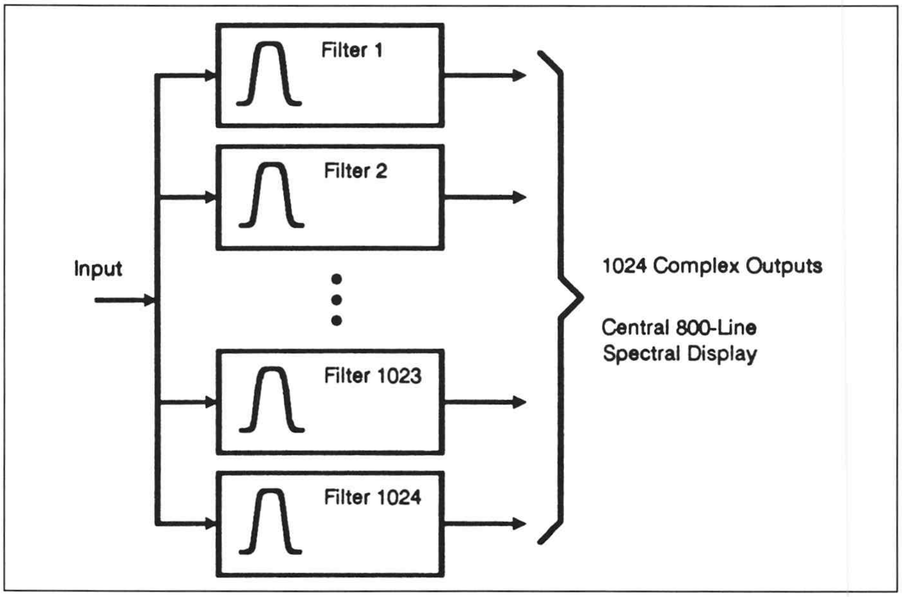


Figure 13. The complex time-domain data is analyzed by a bank of 1024 parallel FIR filters to obtain a spectral frame.

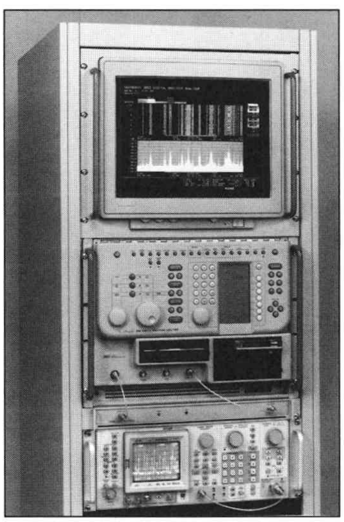


Figure 14. 3052 Digital Spectrum Analyzer shown in rack with RF160 Down Converter and 2756P Spectrum Analyzer.

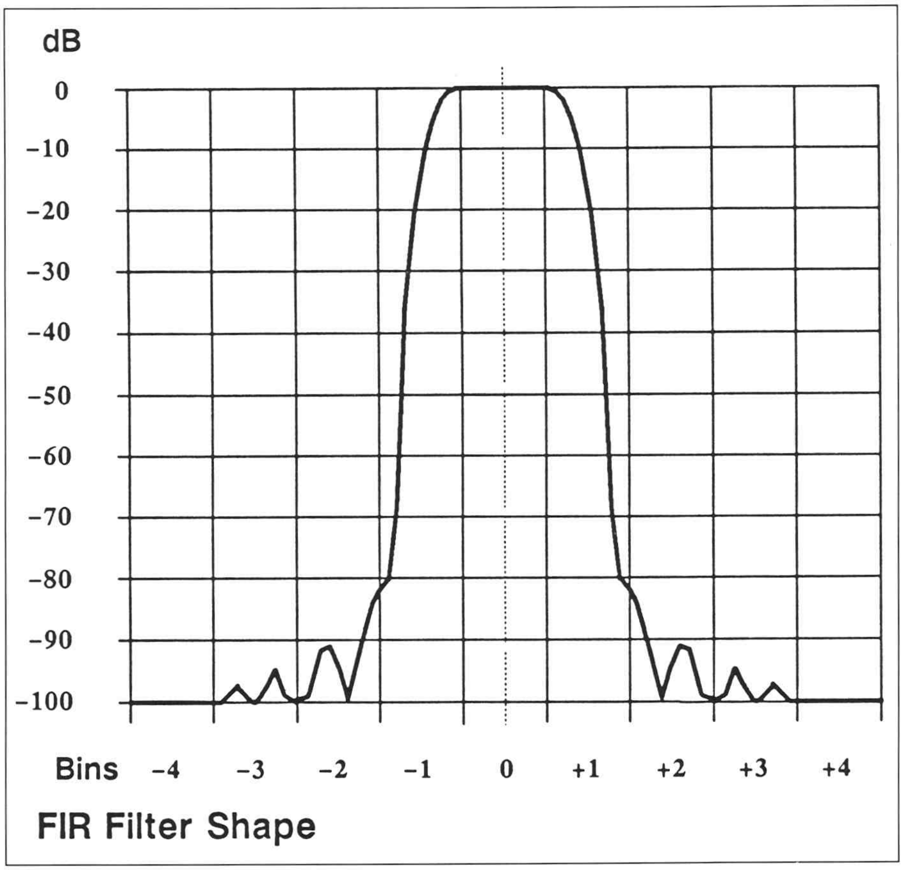


Figure 15. The brickwall filter shape produced by the FIR filters used in the 3052 Digital Spectrum Analyzer.

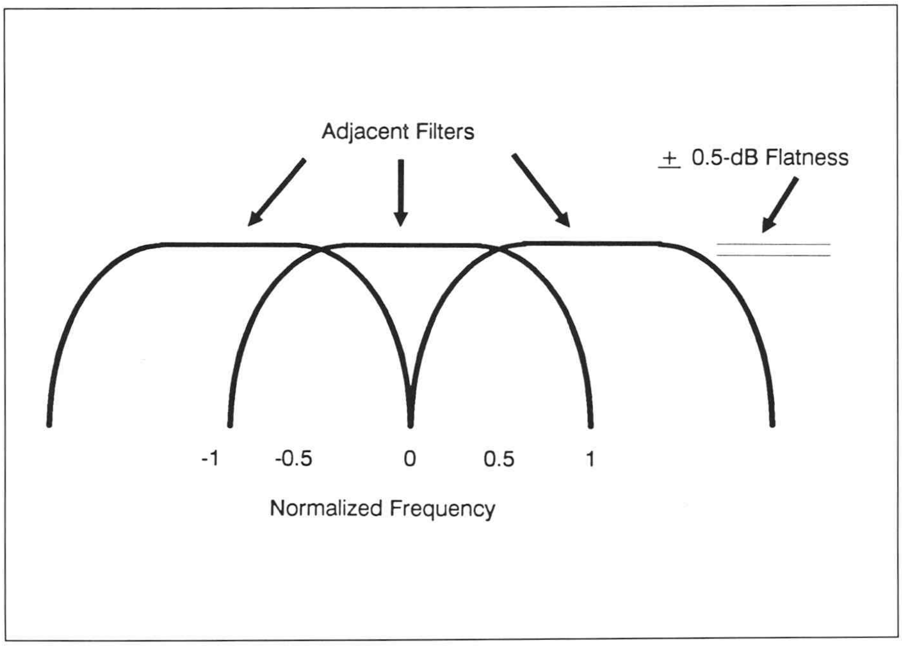


Figure 16. Composite showing FIR filter overlap and resulting flatness.

Not only does the parallel bank of 1024 filters provide high conversion speeds, but it provides exceptional spectral resolution, accuracy, and dynamic range. These attributes are due to the special design of the filters and their brickwall shape. This brickwall response is shown in Figure 15.

Notice in Figure 15 the exceptional flatness of the filter response. This provides a true and accurate measurement of spectral power, not just an amplitude estimate as done with conventional FFT approaches. Also, the band edges are shaped to produce a composite flat response over the instrument's entire span. The sharp skirts or roll-off of each filter result in high spectral resolution and virtually no discernable leakage of spectral energy or data into adjacent bins. These sharp skirts and minimal leakage account for the 3052's high sensitivity, high dynamic range, and high resolution. For example, with the 1-kHz frequency span, two signals having as much as 70-dB power difference and only 4-Hz frequency separation can be clearly resolved.

All of the filters have identical shapes and properties. The only difference is that their center frequencies are offset so that the filter bank provides closely adjacent bin coverage of the selected frequency span. This composite filter bank shape and the bin separation characteristics are shown in Figure 16.

The conversion speed and completeness and quality of the resulting data means that the data is compatible with real-time post-processing.

The parallel nature of the 3052's filter bank is a major contributor to high conversion speeds. Another major contributor is the high-speed parallel processing of the filter outputs. This preliminary processing consists of converting the filter bank's real and imaginary outputs to power and phase spectra for spectral frame displays.

The actual speed of conversion—from analog signal input to update of a spectral frame display—depends on the frequency span selected. **For real-time applications, the output update rate must be twice the resolution filter pass band**. The conversion rates, or frame update intervals, for the various spans provided by the 3052 Digital Spectrum Analyzer are listed in Figure 17 along with an illustration of the concept of display frame updating.

As indicated in Figure 17, real-time frame updating occurs for all spans up to 2-MHz. When the block capture mode is used on spans of 2-MHz or less, blocks of 500 spectral frames are transferred to memory at 200-μS intervals. The block of frames is then transferred to the 3052's color monitor for display in the spectrogram mode. Blocks can be repeatedly transferred for display with the only data loss being during the block memory-to-monitor transfer interval.

The spectrogram display mode, available for real-time frame or block frame capture, is a time sequenced arrangement of spectral frames. Blocks of frames can be held in memory so that frame-to-frame browsing can be done. This browsing is done by simply moving a marker along the spectrogram time scale to select the desired frames for viewing.

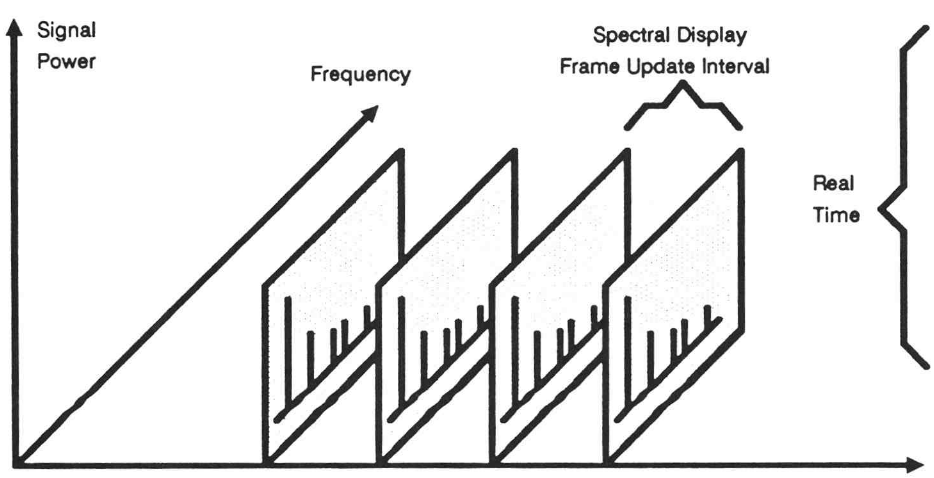
Data Formatting and Display

Because of the high frame update rates available in the 3052, as fast as 200 μS per frame, the amount of continuous spectral information may be far more than necessary for some applications. For such cases, several display summary modes are provided. These include—

- **Rth—**display every Rth spectral frame.
- **Average—**each displayed frame is an average over R frames with each bin containing its average value over the R frames.
- **Peak—**each displayed frame contains the maximum values per bin over R frames.
- **Min/Max—**two frames are displayed simultaneously, one being the maximum bin values over R frames and the other being the minimum bin values over the same R frames.

In addition to the display summary modes, there is a variety of other features that further aid and simplify spectral data capture, tracking, and analysis. Some of the more important features include—

- **Flexible Triggers—**source (internal, external, or line), level, and slope selection along with Start, Single, and Free Run triggering modes.



Span	Frame Update Interval
10 MHz	20μs
5 MHz	200μs
2 MHz	200μs
1 MHz	200μs
500 kHz	200μs
200 kHz	1 ms
100 kHz	1 ms
50 kHz	1 ms
20 kHz	5 ms
10 kHz	5 ms
5 kHz	5 ms
2 kHz	25 ms
1 kHz	25 ms

Figure 17. Updating of spectral frames occurs at real-time rates up through the 2-MHz span.

- **Spectral Event Detection—**A type of selective spectral triggering, this allows upper and lower limit waveforms to be set up for detecting and capturing spectral events falling above or below the limits (optional feature).
- **Intelligent Markers and Signal Processing—** includes a single tunable marker for frequency and power readout, dual markers for delta readouts, and selections for peak find and next right, next left, next higher, or next lower peak. Peak and valley searches can also be done, and there is a bandwidth mode for finding dB-down points on selected lobes.
- **Macro Programming—**any keystroke sequence for set up or processing can be saved as a macro. Macros can be executed by push-button or menu selection.
- **Multiple Display Formats—**spectra can be displayed as power versus frequency, phase versus frequency, spectrogram (power versus time and frequency), and waterfall.
- **Dual Display Windows—** allows simultaneous display of different spectral frames or display modes for comparisons.
- **Color Coded Display—**a high-resolution color monitor provides stratified color coding of power levels for fast and easy visual spotting and tracking of events or trends in the spectrogram displays.
- **Fast Control—**three large knobs on the detachable front panel allow easy spinning through spans, center frequencies, and spectral frames for fast spectral searches or event tracking. Simple push buttons and menu selections allow quick access to other display and analysis features, all of which can be combined into macros for automatic execution.

The Impact on Test and Measurement

The substantial expansion of real-time spectrum analysis to 2 MHz will, by itself, have enormous impact on test and measurement capabilities in a broad range of areas. Certainly, this will be a much sought after capability in the defense, surveillance, and security markets. However, there are just as many equivalent applications in the commercial arena. Commercial radar, navigation, collision avoidance, and communication system development and evaluation can derive the same types of benefits from real-time capture and analysis of short-term or intermittent spectral events that can corrupt or foil system integrity.

Still other application possibilities exist in research and development as well as manufacturing production and automatic test. For example, the real-time capabilities of the 3052 have the potential for providing new insights into laser stability and materials interactions, information that is critical for advances in a wide range of laser processing applications. And, in manufacturing and production test, real-time capture and reduction of spectral data will allow automatic test and verification to be carried out in much greater and revealing detail without compromising throughput.

The extensibility built into the 3052's architecture suggests even greater application possibilities and breadth. Down Converters such as the Tektronix RF160/2782 combination will allow the 10-MHz analysis bandwidth of the 3052 to be applied to any frequency range up into the microwave region. Frequency synthesizers and multiplexers can be analyzed in greater detail for spurious emissions, interband attenuation, etc.

And, for any application area, there are numerous access ports as indicated in the system block diagram shown in Figure 9. For example, an auxiliary Digital I/O port at the A/D converter can be used to export digitized signals from the 3052 to other analysis equipment. Or digitized signals from other sources can be imported to the 3052 for spectral analysis. The same kinds of import/export capability are also provided downline in the 3052 at the output of the Digital Down Converter and after the filter bank at the power and phase evaluation stage. This latter access port allows unreduced spectral frame data to be routed directly into other digital processing equipment such as a mainframe scientific computer, an ATE processor, or a factory automation and archiving system. An Event Detect output is also available for triggering other external processes or actions based on spectral events detected by the 3052.

All of these are just a few of potential possibilities suggested by the many capabilities provided by the new 3052 Digital Spectrum Analyzer. However, as with any significant advance in measurement capability, a far greater number of applications and new possibilities will become apparent as use of the 3052 becomes more widespread.